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Energy requirements of thin-film solar cell modules—a review

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Abstract

In this paper a number of energy analysis studies for thin-film solar cell modules are compared and reviewed. We start with a short introduction into methodological issues related to energy analysis (of PV systems) such as system boundary definition, treatment of different (secondary) energy types and the choice of functional unit.

Subsequently we review results from 6 studies on a-Si modules and 3 studies on CdTe modules. The aim is to present results in a unified format, compare them and try to clarify observed differences. Although significant differences were found, many of these differences could be explained by the choice of materials for the module encapsulation. For categories with large observed differences, like indirect process energy and capital equipment energy, we performed additional analyses in order to gain a better understanding of these aspects.

Finally we present 'best estimates' of the energy requirement for present-day a-Si and CdTe thin film modules which are between 600 and 1500 MJ (primary energy) per m^2 module area, depending on cell and encapsulation type. This means that the energy pay-back time is below two years for a grid-connected module under 1700 $kWh/m^2/yr$ irradiation. In the near future an energy pay-back time below one year seems feasible. © 1998 Elsevier Science Ltd. All rights reserved.

1. Introduction

Research on photovoltaic systems for terrestrial applications was started in the 1970's against the background of the 'energy crisis'. Although the background issues have changed over the past decennia PV technology was and still is considered as a technology which can reduce our dependence on fossil fuels. Nowadays it is the issue of climate change and the need for CO_2 mitigation which is the main political driving

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force behind the photovoltaic R&D programmes around the world. Somewhat boldly, one might say that the need for energy saving and CO_2 mitigation is the reason for the existence of terrestrial PV technology[1].

In view of this motivation for photovoltaic R&D funding, one can rightfully demand from PV systems, or at least from grid-connected PV systems, that:

- the systems generate more energy over their life time than their production, installation and removal requires.

Because in our time not fossil fuel resources but climate change is the main policy issue, one can broaden the requirement and reformulate it in Life Cycle Assessment terminology as:

- the emissions of greenhouse gasses from the PV system life cycle should be as low as possible, and at least lower than the emissions from competing fossil fuel options.

The first question may be addressed by means of an energy analysis, in which all energy inputs are accumulated over the entire production process for PV modules and BOS components, as well as over the installation and removal processes. These accumulated energy inputs in relation to the yearly energy generation by the PV system can subsequently be expressed as the 'Energy Pay Back Time' of the PV system.

The second question requires a more extensive analysis in which all emissions of CO_2 and other greenhouse gasses are evaluated over the PV system's life cycle. Although energy-related emissions of CO_2 mostly dominate in such an evaluation, there may be cases where emissions of for example the greenhouse gasses SF_6 or CF_4 from plasma reactors are quite significant [1].

In this paper however, we will restrict ourselves to an analysis of energy requirements only, because data on non-CO_2 greenhouse gas emissions from a PV system life cycle are still rather scarce.

Apart from providing a foundation for energy policy decisions, there are other motivations for performing an energy analysis of PV systems. In the first place the environmental effects from conventional energy production are often quite significant, so an energy analysis can give a first indication of the 'environmental profile' of PV systems.

Secondly an energy analysis may be helpful in identifying energy reduction options in the design and manufacturing of PV module or BOS components.

Summarizing, we can say that an energy analysis can give insight in:

- the overall generating efficiency of PV systems;
- the potential for CO_2 mitigation by PV;
- the energy-related emissions of PV manufacturing.

Doubts regarding the energy balance of PV systems are sometimes expressed in popular accounts on the prospect of solar energy. This doubt may date back to a

[1] Of course, a second important reason for the interest in PV systems, is the 'energy service' which they can supply at isolated locations, for example in the form of Solar Home Systems.

1972 paper in which the energy pay-back time of a PV system was calculated to be 40 years [2].

Since then a fair number of energy analysis studies for PV modules or systems have been published [3–16], but—as we will see below—with varying approaches and with significant variation in the results.

This is not a very satisfying situation and therefore our aim in this paper is to bring some clarity in the issue of the energy pay-back time of PV systems. For this purpose we will first discuss some methodological aspects of energy analysis in relation to photovoltaic energy systems (section 2) and review a number of energy analysis studies on *thin-film photovoltaic modules* (section 3). By comparison of the estimates from different authors and by performing some additional analyses, we will try to come to better understanding of the reasons for the differences. Then we will make a best estimate of the energy requirements and energy pay-back time of thin film modules and discuss future prospects (sections 4, 5 and 6). Finally we will draw conclusions and give some recommendations to both manufacturers and energy analysts.

In this paper we will restrict ourselves to *thin-film modules* because:

- thin-film technology is considered to be a very important option for future, low-cost PV modules;
- a fair number of energy analysis studies has been performed on thin-film modules;
- results from these studies show a considerable variation;
- given the small amount of cell material in thin film modules one might expect that the choice of cell material has a small effect on the total energy requirement for the module.

Discussions of the energy requirements for PV systems based on crystalline silicon modules and including BOS components can be found in for example [17–19].

2. Methodological issues

In the course of our evaluation and comparison of different energy analysis studies we encountered some problems which stemmed from methodological choices and from incomplete reporting of assumptions.

For this reason we will start with a short discussion of some methodological issues and other significant assumptions which need to be reported in an energy analysis of a PV system. We will finish this methodology section with some definitions, among which a definition of the 'energy pay-back time'.

The assumptions underlying an PV system energy analysis fall into three main categories: characteristics of the PV system itself; assumptions about the 'manufacturing environment' and choices concerning the 'analytical framework'.

2.1. *PV system characteristics*

The specification of PV system characteristics should include items like:

- PV module production technology;
- type of module encapsulation, frame and array support;
- module size and efficiency;
- BOS components;
- PV system application type: e.g. grid-connected or autonomous;
- PV system performance characteristics, these can be given as e.g. the irradiation at the system site and the Performance Ratio.

We assume that these parameters need no further elaboration, although we want to stress the importance of specifying the type and quantity of frame material for a PV module.

2.2. *Manufacturing environment*

Important characteristics about the 'manufacturing environment' which should be reported in energy analysis study are:

- the average conversion efficiency of the electricity supply system;
- the status of non-PV technologies, i.e. the energy requirements for production of commodities like glass, aluminium and steel.

If one wants to follow up the energy analysis by an evaluation of the CO_2 mitigation potential one will also need to specify:

- the fuel mix of the electricity supply system.

The conversion efficiency of the electricity supply system may vary considerably between different countries, but very often an average value of 0.35 is used. Transmission and distribution losses may be incorporated in this figure if it is clear that the PV electricity is consumed in the immediate vicinity of the PV system. Another point one may want to take into account concerns the differences between the 'manufacturing country' and the 'application country' (see for example Ref. [20]).

Basic data about the energy requirements for commodities may also vary significantly with the country and the year of the underlying study. So the assumed values should always be reported clearly.

The same remarks apply to the fuel mix data for the electricity supply system. Therefore it can in some cases, be convenient to define a generic fuel mix based on averaged data. Also one might consider to base the fuel mix data on a next generation of electricity production equipment which may be assumed to be the main competitor of PV in future capacity expansion.

2.3. *Analytical framework*

The 'analytical framework', finally, described the scope and the methods used in the analysis. There are four issues that we want to discuss:

- the choice of functional unit;
- the treatment of different energy types;

- the system boundary or analysis level;
- allocation methods.

2.3.1. *Functional unit*

The functional unit in an LCA or energy analysis describes the unit of end-product to which the energy requirements will be related. The best choice for the functional unit will depend on the objectives of the study. Possible functional units in our context are:

- 1 kWh of electricity produced by the PV system (see for example Ref. [21]);
- 1 Wp of module power;
- 1 m^2 of module area;
- 1 m^2 of cell area;
- 1 module.

Of course the kWh and—to a lesser extent—the Wp are the most *functional* of units because they are directly related to the end-user service. The disadvantage of the kWh or Wp units is that this choice introduces extra parameters, namely irradiation, PV system performance and module efficiency, which have no or little relation to the energy consumption during module production.

It is obvious that most energy requirements for module production, like energy for material consumption and energy for processing are in the first place area-dependent. Very often the efficiency of a module and thus its power rating may be enhanced by a subtle change in the production process without a significant increase in the energy consumption. So given our objective of comparing different modules or different energy analysis studies, an *area* unit will be the most convenient functional unit[2].

The choice between *module area* or *cell area* is less important although for crystalline silicon technology, the unit of cell area has some advantages.

The *module*, finally, is an inconvenient functional unit because modules do not have a standard size or power rating.

In this paper we will use the *module area* as our functional unit.

2.3.2. *Different energy types*

The energy consumption in a production process may be distinguished into two main categories of secondary energy: thermal energy and electrical energy. Sometimes a third category is added of 'non-energetic' or 'feedstock' energy, which accounts for the heating value of an input material if this material may also be applied as an energy carrier. In the manufacturing of plastics, for example, the contribution of this feedstock energy may be considerable. In PV module production, however, feedstock energy typically contributes only a few percent to the total energy requirement [5].

The amounts and types of primary fuels used for the production of these secondary energy forms will be quite different for each secondary energy form, but may also

[2] Strictly spoken this is no longer a *functional* unit, because area coverage is hardly a function of a PV module.

differ among production sites. This means that not only the conversion efficiencies but also the environmental effects will show large differences. Therefore it is recommendable to consider at least the thermal and electrical energy forms separately throughout the entire energy analysis.

In order to allow direct comparison of energy data one can convert them to the 'Equivalent Primary Energy' (EPE)[3] by applying the respective conversion efficiencies for thermal and electrical energy so that one obtains the corresponding primary energy input (see also Fig. 1):

$$E_{\mathrm{EPE}} = E_{\mathrm{el}}/\eta_{\mathrm{el}} \quad \text{or} \quad E_{\mathrm{EPE}} = E_{\mathrm{th}}/\eta_{\mathrm{th}}$$

In our review of energy analysis studies below we will give results in EPE terms only because most of the considered studies did not distinguish between electrical and thermal energy in their presentation of results.

2.3.3. *System boundary*

The system boundary demarcates those production processes which are taken into account in the energy analysis from those that are not accounted. Often the system boundary is defined in terms of the IFIAS scheme of orders ([22], see Fig. 2), so that for example an analysis up to order 3 incorporates also the energy used for manufacturing the capital equipment.

The studies reviewed below are either order two or three, therefore we will present results up to order three.

What the IFIAS order definition does not yet specify, is which input materials are accounted and which stages in the product life cycle are considered. In analyses of PV module production the production of ancillary materials like carrier and purging gasses, cleaning fluids, solvents, etc. is usually left outside the system boundary

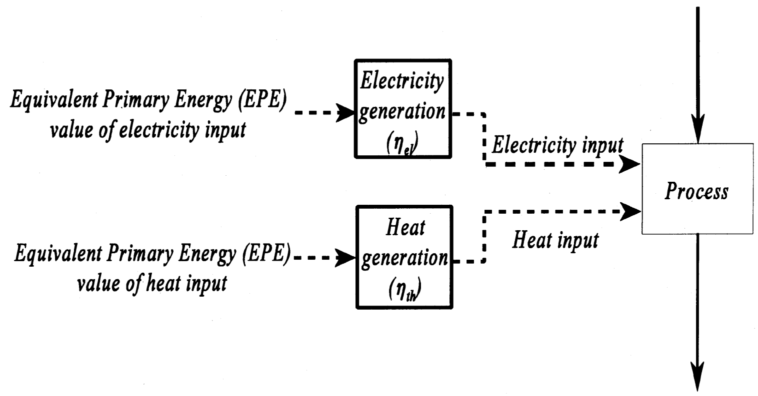

Fig. 1. Illustration of the concept of Equivalent Primary Energy.

[3] Sometimes the subscript 'th' or 'thermal' is used with energy data, when in fact 'Equivalent Primary Energy' is meant.

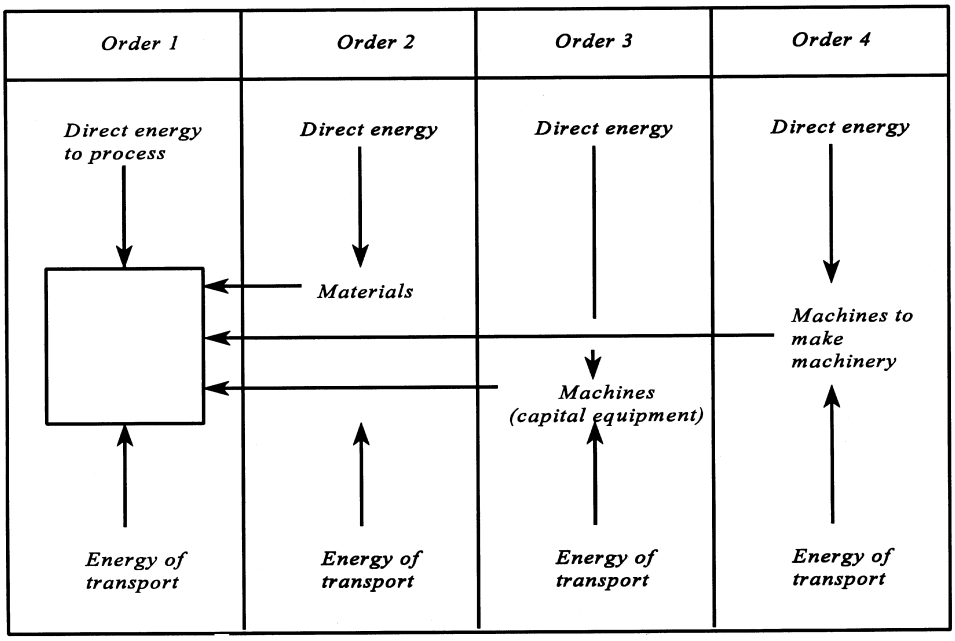

Fig. 2. IFIAS scheme of orders in energy analysis [22].

because: (a) there are almost no energy data for these materials and (b) the consumption of these materials is relatively small.

For similar reasons the life cycle stages of PV system installation, maintenance, decommissioning and waste treatment are usually left out of consideration too. Also the energy requirement for transportation of materials is usually left out of the evaluation.

We will return to the issues of transportation and recycling later.

2.3.4. *Allocation methods*

It may happen that a certain process within the system boundary has two or more output products. In that case the cumulative energy input of all the upstream processes will have to be divided among the different products (see Fig. 3). There are different possibilities of how to perform this 'allocation' of energy requirements between the process output products, for example:

(1) regard only one main product and allocate all energy to this single product;
(2) allocate the energy requirements on basis of the mass of the different products;
(3) allocate on basis of economic value or another parameter describing the 'quality' of each product.

It is not possible to identify a best allocation method, the actual choice will depend on the type of products and the aim of the study. Of course the chosen allocation method should preferably be based on some kind of guiding principle, for example

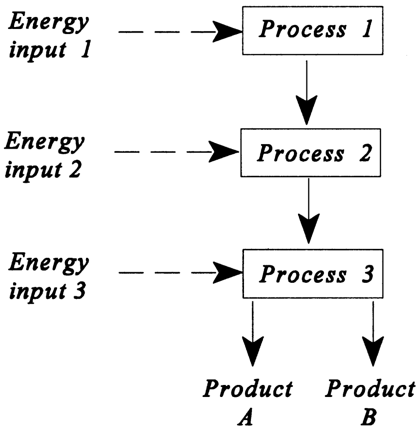

Fig. 3. Sample process stream in which the cumulative energy input has to be allocated between the output products A and B.

causality. In the latter case one should ask: "which product may have caused which part of the energy input". In any case the chosen allocation method must be reported clearly.

A relevant example is the production of silicon wafers, where most of the wafers are destined for the semiconductor industry, but a certain percentage, the 'off-spec' wafers, is sold to the PV industry. It has been shown that just by choosing different allocation methods the total energy requirement which is calculated for a monocrystalline silicon module can vary between 4160 and 15,520 MJ/m^2 [23]. The allocation on mass basis, which may be the best method[4] in this case, yielded a value of 11,670 MJ/m^2 (as Equivalent Primary Energy).

With regard to thin-film module manufacturing such allocation issues may arise with the production of cadmium or tellurium, which are obtained as a by-product of zinc or copper mining.

Fortunately, in this case the choice of allocation method has negligible impact on the total energy requirement of the module.

2.4. *Definition of gross energy requirement and process energy requirement*

Two terms which are used often in energy analyses are the Gross Energy Requirement (GER) and Process Energy Requirement (PER).

The Gross Energy Requirement refers to the total amount of primary energy incorporated in a product, as a result of all the production processes necessary to manufacture it. The GER of a product will include the feedstock energy (if relevant).

The energy required in a specific process step is called the Process Energy Require-

[4] Actually an allocation based on both weight and quality might be fairer in this case, because it may be argued that the off-spec wafers have 'caused' less energy consumption than the IC-quality wafers.

ment (PER). For practical purposes this PER is often separated into a *direct* process energy requirement and an *indirect* or *ancillary* process energy requirement. The first quantity gives the electrical and fuel energy which is consumed directly by the production equipment itself, while the ancillary process energy represents the energy used for ancillary operations such as lighting, heating and ventilation. Note that the latter quantity does not comprise the energy losses due to secondary energy production (e.g. electricity production), these losses are accounted for by the conversion to EPE values.

Cumulation of all PER values for the subsequent process steps in a production process and summation with the feedstock energy of the input materials results in the GER value of the final product (see Fig. 4).

2.5. *Definition of 'Energy Pay-Back Time'*

The Energy Pay-Back Time is an indicator which is very frequently used to evaluate the energy balance of energy production systems. Often the energy pay-back time is loosely defined as the energy input for the manufacturing of the PV system divided by the yearly energy production of the system.

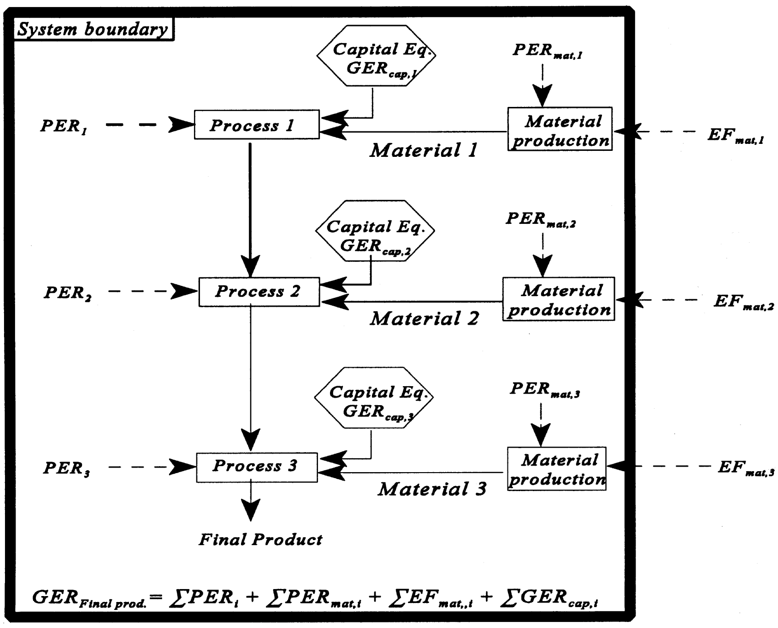

Fig. 4. Illustration of the calculation of the GER value of a final product in an energy analysis of order 3. The GER is calculated as a sum of the energy inputs per process step (PER_i), the energy requirements for each input material ($PER_{mat,i} + EF_i$) and the energy requirements for the capital equipment ($GER_{cap,i}$).
PER = Process Energy Requirement;
GER = Gross Energy Requirement;
EF = Energy Feedstock, i.e. the Heating Value of a feedstock that is regarded as an energy carrier.

A more exact formulation looks at all energy inputs in the complete PV system life cycle and calculates all energy in- and out-puts back to their Equivalent Primary Energy value:

$$\text{Energy Pay-Back Time (EPTB)} = \frac{E_{input}}{E_{gen}}$$

with:

E_{input} = primary energy input during module life-cycle $= E_{man} + E_{trans} + E_{inst} + E_{use} + E_{decomm}$

E_{man} = primary energy input during module manufacturing (incl. resource mining);

E_{trans} = primary energy input during material and module transportation;

E_{inst} = primary energy input during module installation;

E_{use} = primary energy input during module operation;

E_{decomm} = primary energy input during module decommissioning;

E_{gen} = primary energy savings due to yearly electricity generation by PV module.

Note that the definition of E_{gen} above can be used to take into account certain subleties regarding the total electricity production system. For example when electricity generation by a PV system does not necessarily result in primary energy savings because not all of the PV electricity may be fed into the grid for some reason. Also it can account for the specific conversion efficiency of those electricity generating units which are displaced by the PV production (e.g. gas turbines).

Obviously the value of E_{gen} is very much dependent on the irradiation and overall system performance. Therefore EPBT values should always be reported along with the assumed irradiation and Performance Ratio.

One advantage of the EPBT indicator is that it is additive, EPBT values for different system components may simply be added up to obtain the total system EPBT. A disadvantage, on the other hand, is that it does not give an indication of the net energy balance over the system's life time. For this purpose an Energy Yield Factor or Energy Return Factor may be defined as:

$$\text{Energy Return Factor (ERF)} = \frac{E_{gen} \times L}{E_{input}} = \frac{L}{EPBT}$$

with L = the life time of the PV system.

With this definition an Energy Yield Factor of 3 would mean that the PV system produces three times the amount of energy which is consumed in its life cycle. A disadvantage of the ERF indicator is that it is not additive, in contrast to the EPBT.

3. Review of energy analysis studies for thin film modules

3.1. *Introduction*

We will now present a review and comparison of a number of energy analysis studies for thin film modules. Our objective of the review is to:

- compare study results;
- identify areas of agreement/disagreement/uncertainty;
- obtain a ‘best climate’ for energy requirement of thin film modules;
- compare a-Si and CdTe results;
- identify points of attention (‘hot spots’).

For this purpose we have selected the following 6 studies on a-Si modules and 3 on CdTe technology.

The study by Hagedorn et al. on a-Si (and other) modules [4, 5, 24] is the oldest but still one of the best in the field. While the study published in 1989 was based on design plans for a production facility, actual measurements underly the 1992 study. We used the latter data only, which are given in some detail in [24].

More or less in response to the high results from the first Hagedorn study, Palz and Zibetta [9] published an evaluation for the a-Si plant of Chronar France.

Van Engelenburg and Alsema [13, 15] used the Hagedorn study as a starting point for an evaluation of three future variants for a-Si technology. Here we will use their ‘worst case’ data only which closely follows Hagedorn.

Srivinas et al. published a study based on two operating a-Si facilities in Yugoslavia and India [10, 28]. The results obtained at these two sites were translated by Srivinas to a single, typical configuration under European climate conditions.

Kato and co-workers [11, 23] published results from an extensive study on different module types and for present-day as well as future production technology, on the basis of Japanese data. Only the results for the ‘present-day’ 10 MWp production plant are reviewed here.

Lewis and Keoleian [16, 25] studied the energy pay-back time for the 0.4 m^2 a-Si tandem junction module produced by United Solar Corp. (UPM 880). This study is the only one to explicitly include transportation energy.

Regarding the CdTe solar cells, actual data from module production are not yet available, so only three desk-top studies could be examined, authored by respectively Hynes [8], Alsema and Van Engelenburg [12, 15] and Reetz [26, 27]. Table 1 below gives an overview of the studies along with some details on the module layout and production processes.

3.2. *Method of approach for the comparison*

In order to allow comparison of the results from all these studies we first had to define a common format for presentation of their results.

As almost every study used a different set of energy and/or functional units our first step was to convert all results to a common basis. As argued above we choose for MJ of Equivalent Primary Energy per m^2 of module area as the basic unit. Unfortunately it was not possible to maintain a separation between thermal and electrical energy[5].

[5] For the conversion efficiency for electricity production we used a value of 0.35, which corresponds to the values used in most original studies too. In case thermal energy consumption and ‘feedstock energy’ were given separately (Hagedorn study only) we used Hagedorn’s values of 0.85 respectively 0.80 for the conversion efficiency to obtain the primary energy equivalent.

Table 1
Overview of energy analysis studies for a-Si and CdTe modules

	a-Si						CdTe		
	Hagedorn	Alsema	Palz/Zibetta	Srinivas	Kato	Lewis/Keoleian	Alsema	Hynes	Reetz
Year of publication	1992	1993/1996	1991	1991	1995/1997	1996/1997	1992/1996	1994	1993
Refs.	[5, 24]	[13, 15]	[9]	[10, 28]	[23, 29]	[16, 25]	[12, 15]	[8]	[26, 27]
Module structure	Glass	Glass	Glass	Glass	Glass (cover)	Tefzel	Glass	Glass	Glass
	TCO	TCO	TCO	TCO	EVA	EVA	TCO	TCO	TCO
	a-Si	a-Si	a-Si	a-Si	Glass (substr.)	TCO	CdS	CdS	CdS
	Ag/Ni	Al	Al	Al	TCO	a-Si	CdTe	CdTe	CdTe
	EVA	EVA	Polymer	Polymer	a-Si	Back reflector	Back contact	Cu/Mo	ZnTe/Al
	Glass	Glass			EVA	Stainless steel (substr.)	EVA	EVA	EVA
					Tedlar	EVA/polymer Steel back plate	Glass	Glass	Glass
glass thickness (mm)	3/3	3/3	?	3	2/3.2	–	3/3	3/3	3/2
Frame[1]	Al/none	None	Polymer?	Polymer/none	Al/none	Al/none	Al/none	?	None
deposition process[2]:									
– window	PECVD	PECVD	PECVD	PECVD	PECVD	PECVD	ED	CB	CSS
– absorber	PECVD	PECVD	PECVD	PECVD	PECVD	PECVD	ED	ED	CSS
– back contact	Sput	Evap	Evap	Evap	Sput	ScrPr	Evap	Sput	Sput
data source	German a-Si plant	Literature	Chronar-France	Rade-Koncar + BHEL-India	Sanyo and others	United Solar Corp. (UPM 880)	Literature	Lit. + own expertise	Lit. + Battelle Inst.

[1]In a number of studies the energy data are also given without a frame, this indicated by 'Al/none' or 'polymer/none'.
[2]Abbreviations: PECVD = Plasma Enhanced Chemical Vapour Deposition, ED = Electro Deposition, CB = Chemical Bath, CSS = Close-Spaced Sublimation, Sput = Sputtering, ScrPr = Screen Printing, Evap = Vacuum evaporation.

Secondly we had to define the general categories into which we would like to distinguish the energy consumption. These categories had to be compatible with the categories used in the original studies. In line with our own previous studies and the categories used by Hagedorn, we distinguished five categories of energy consumption for the module manufacturing process:

- Cell Material, i.e. the Gross Energy Requirement of all materials used for the preparation of the solar cell itself (semiconductor material, contact layers, etc.).
- Encapsulation Material, i.e. the Gross Energy Requirement of all materials used for:
  —the substrate for the solar cell;
  —the encapsulation of the module (glass, EVA);
  —the junction box and/or connection cables.

Note that whenever possible we *excluded* the materials for the module *frame* from this category.

- Frame, i.e. the GER of the materials for the module frame. We have two reasons for looking at the frame separately. In the first place framing materials can be very different from manufacturer to manufacturer and more in general framing requirements will depend heavily on the module dimensions and the intended application. The second reason is that in most studies the frame comes out as one of the largest 'energy consumers', so it seems useful to look at it separately.
- Direct Process Energy, i.e. all energy directly used by the processing equipment in the module production plant.
- Ancillary Process Energy, i.e. all 'overhead' energy consumption in the module production facility, for example for space heating and cooling, ventilation, emission control equipment. (A more extended discussion on the definition of this category will follow below.)
- Capital Equipment, i.e. all energy used for the manufacturing of the capital equipment used in the module production plant (production machinery, buildings).

In preparing the overview of study results no attempts were made to correct for differences in the basic assumptions (glass thickness, etc.) or to make category divisions which were not present in the original study reports.

3.3. *Overview of study results*

The results for all energy analysis studies in the common set of units and the categories outlined above are given in the overview table below (Table 2).

As mentioned before the frame energy requirements are excluded from the data for the module whenever possible (not for the Palz/Zibetta and Hynes studies) and then reported separately in the single row at the bottom.

Also we should remark that not in all cases all energy categories could be distinguished or given a value. Especially the Ancillary Process Energy could not always be derived from the study report as a separate value. Furthermore the energy requirement for Capital Equipment was not always estimated.

Table 2
Energy requirements for a-Si and CdTe modules (excl. frame) as found by different authors, in MJ of Equivalent Primary Energy per m^2 of module area. Data for frame material energy are given separately in last row

	a-Si							CdTe	
Author Encapsulation	Hagedorn glass/glass	Alsema glass/glass	Palz/Zibetta glass/polymer	Srivinas glass/polymer	Kato glass/Tedlar[a]	Lewis Tefzel/Steel[a]	Alsema glass/glass	Hynes glass/glass	Reetz glass/glass
Cell material	32	18	*	38	458	26–29	–	11	11
Encapsulation material	429	278	228[b]	209	395[c]	365–611	278	591[d]	244[e]
Processing direct	320	1150[f]	274	538	416	490	129	336[f]	550
Processing ancillary	803	*	206	198	76	–	235	*	610
Capital equipment	396	443	–	0	9	–	443	54	–
Total	**1980**	**1889**	**708**	**983**	**1354**	**881–1130**	**1085**	**992**	**1415**
Frame	–	175	?	± 50	289	480–1350	–	?	–

Symbols:
– = category is explicitly excluded from study; 0 = found to be negligible; ? = not detailed or unclear in study; * included in data for other category.
Notes:
[a]deviating module structure: see Table 1; [b]includes cell material and probably also the frame; [c]includes 100 MJ for the glass substrate (in Kato's publication this item was incorporated in the cell material category), furthermore the energy for the A1 frame is excluded here; [d]includes frame; [e]includes transportation and auxiliary materials; [f]also includes ancillary processing energy.

If we first look at the resulting total energy requirements for an a-Si module, we see a considerable variation from 708 MJ/m^2 (Palz/Zibetta) to 1980 MJ/m^2 (Hagedorn). The estimates for CdTe modules stay within this range. And even if studies have some agreement for the total values then the distribution over the categories may show marked differences.

This clearly is a very unsatisfactory situation and we would like to get more insight into the possible reasons behind these differences. Therefore we will now look in more detail at the data for each category.

3.4. *Energy for cell materials*

As may be expected for thin film cells the energy incorporated in the cell materials is very low, for both considered cell types. With one exception the Gross Energy Requirement for these materials is estimated to be below 40 MJ/m^2. In Kato's study quite a large energy requirement is found of 458 MJ/m^2, which is mainly due to the TCO layer (350 MJ/m^2). This latter value is the result of a very high assumption for the GER of $SnCl_4$ (2000 MJ/kg) combined with a very low material utilization (5%), both of which we consider much too pessimistic. For example, for sputtering of TCO layers a material utilization rate of 30–40% has been estimated [30].

The differences between cell types (a-Si and CdTe) are not very significant: although the layer thickness in CdTe cells is higher, the electrodeposition process has a much better material efficiency. Because of the low content of active cell material the influence of uncertainties in the energy data for materials like cadmium and tellurium will also be insignificant.

On the whole an energy requirement for all the cell materials of less than 40 MJ/m^2 in a-Si modules seems reasonable for today's process technology. However, if the layers are thicker than assumed here ($<10\ \mu$m), for example in screen-printed cells, and if very high purity material is required the energy requirement may increase substantially.

3.5. *Energy for encapsulation materials*

Under encapsulation materials we understand here all materials, outside the active cell layers and contact layers, and also excluding the module frame. This means that for the UniSolar module (Lewis/Keoleian) and the module studied by Kato the substrate materials are also included in this figure, even though they are not part of the encapsulation in the strict sense.

Generally spoken, the encapsulation materials constitute a very important part, up to 50%, of the total energy requirement. Although the estimates for the encapsulation material energy show a very wide range, most differences can be explained by the choice of encapsulation materials and, to a lesser extent, by the assumed GER values for the encapsulation materials.

To start with we exclude from our comparison the Palz/Zibetta and the Hynes studies because they probably include a frame in the encapsulation materials.

For the remaining studies we see that the lowest value of 200 MJ/m^2 is found for a glass/polymer encapsulation while the highest estimate of 600 MJ/m^2 is for the Unisolar module which incorporates a steel substrate in addition to a steel back plate and a Tefzel cover.

Noticeable for this latter module is further the relatively high energy requirement of 200–270 MJ/m^2 for 'other encapsulation materials' outside the steel substrate and the steel backing plate [16]. It is not clear if this is mainly for the Tefzel cover or, for example, the junction box is responsible. Given the rather high GER value for Tefzel (our estimate: 75 MJ/kg [31]) we see that the choice for a polymer as module *cover* material does not necessarily lead to a reduction in energy use.

A similar situation is found in the study by Kato where additional PVF, Al and EVA layers increase the energy requirements by some 80 MJ/m^2.

Another point to note is that there is a rather broad range in the GER values for glass sheets, from 15 MJ/kg (Alsema) to 25 MJ/kg (Srivinas). It should be kept in mind that the energy consumption for production of glass (and for other commodities) has been reduced considerably over the past decades. So one should be careful not to use energy data which are outdated. Fairly recent data on gross energy requirements may be found in for example [32].

In Appendix 1 we have collected a number of GER values for module materials.

According to our estimates chemically hardened sheet glass of 3 mm thickness can be produced at 15–20 MJ/kg [31, 33] leading to an energy requirement of 120–160 MJ/m^2 for a single glass sheet.

Thinner glass sheets will have lower energy requirements. The use of secondary (recycled) glass, however, is problematic for sheet glass and would only have a small effect on energy use (see section 3.10).

Looking at the Srivinas and Palz/Zibetta studies it seems that the choice for a polymer back cover instead of a glass sheet can be advantageous from an energy point of view. In case of CdTe and CIS modules, however, we recommend a glass/glass encapsulation because it helps to reduce heavy metal emissions [15].

We have also found that the contribution from EVA in the encapsulation is modest (around 40 MJ/m^2 for a 0.5 mm EVA layer).

Finally, if we look at the energy data for glass and EVA above and allowing 10–50 MJ for 'other materials' (wiring, etc.) we can conclude that the energy requirement for encapsulation materials employing two glass sheets (2×3 mm) will be in the range of 300–400 MJ/m^2.

For a glass/polymer encapsulation the energy requirement will be somewhat lower: 170–250 MJ/m^2.

3.6. *Energy for the module frame*

The energy requirement of the module frame is often a very significant contribution to the total energy requirement of a PV module, especially for aluminium frames. Note that in the latter case the energy requirement value includes both the material

energy for the aluminium itself and the process energy for extrusion and anodizing of the Al profiles[6].

The estimates of the frame energy found in the reviewed studies range from about 50 MJ/m^2 (Srivinas) to 500 MJ/m^2 (Lewis/Keoleian), a difference which is mainly caused by material choice (polymer vs aluminium) and material weight.

Obviously the choice of frame materials is dependent on the specific installation type. For example in roof-integrated systems modules without frame can be employed, while in ground-based arrays a frame may be necessary for fastening the modules to the support structure. For this reason we recommend to evaluate the frame energy requirements in the context of the application type and the BOS energy requirements per application.

A second recommendation at this point is that the choice of framing material and the related energy input should always be specified explicitly in energy studies of PV modules. We have noticed that three out of the eight studies reviewed here did not specify the module frame data.

3.7. *Direct process energy*

Most studies do give a separate value for the direct process energy, probably because this parameter is the most easily measured in an actual plant. Also in many cases a subdivision is given for the various process steps in module manufacturing.

For a-Si modules the estimates for the total amount of direct process energy show a modest variation from 270–540 MJ/m^2. For CdTe production by way of electrodeposition the direct process energy is estimated considerably lower: 130 MJ/m^2 by Alsema and less than 300 MJ/m^2 by Hynes et al. This is not surprising in view of the type of processes employed in a-Si deposition (significant energy demand for pumping and substrate heating) as compared to electrodeposition of CdTe. For CdTe production by way of the Close-Space Sublimation process Reetz estimates a higher value of 550 MJ/m^2, probably because of the higher processing temperatures.

We will now restrict ourselves to a-Si manufacturing and compare the estimates from different authors for the separate process steps (Table 3). When we do this we see the agreement which appeared to exist for the total value of direct process energy, becomes less convincing if we look at the process-level break-down. This may of course reflect differences in the actual processing for the different plants which were investigated by the authors, as may for example be the case for TCO deposition and encapsulation. For encapsulation processes the type of encapsulation is clearly very important, with the laminated glass/glass modules being in the disadvantage. Still the value of 2 MJ/m^2 for the encapsulation process which is given by Palz and Zibetta seems hard to believe.

What can we conclude from this? First that there can be a significant variation in the direct process energy requirement not only for different cell types, but also for the

[6] A recent estimate of the GER for primary Al is 187 MJ/kg [32], while the process energy for extrusion and anodization is estimated at about 30 MJ/kg [25, 31].

Table 3
Direct Process Energy for production of a-Si Modules (MJ/m^2)

Process step	Hagedorn	Palz & Zibetta	Srivinas	Lewis &Keoleian
Substrate wash	29	–	–	56
TCO dep.	–[1]	111	207	80
a-Si dep.	109	72	141	92
Back contact dep.	80	56	117	74
Encapsulation	80	2	41	137
Other	22	33	32	51
Total	319	274	538	490

[1]TCO-coated glass is used as input material in the Hagedorn case, energy for TCO deposition is probably included in the glass data

processes employed by different a-Si module manufacturers. Secondly, it appears that the variation in the total value of the direct process energy for a-Si modules might even have been larger than the values given in these studies (the summation of the lowest estimates per process step gives us 260 MJ/m^2, while the highest values add up to 700 MJ/m^2).

One might be tempted to conclude that there is room for optimization with regard to the process energy requirement of a-Si manufacturing. However, in my opinion such a conclusion is too easy as it overlooks the differences that probably exist between the employed substrates, deposition processes and encapsulation methods.

On the other hand, future increases in a-Si deposition speed will probably reduce the direct process energy requirements as the energy consumed by vacuum pumps and substrate heating is mainly dependent on the processing time.

3.8. *Ancillary process energy*

The estimation of ancillary process energy is a very difficult issue. Firstly the demarcation of the system boundary is rather difficult. In practice the category of ancillary process energy seems a sort of reservoir of all energy consumption figures which are not due to the processing equipment itself.

Hagedorn in his study distinguishes 'process-related ancillary energy (e.g. emission control) and general ancillary energy use (climate control, lighting, etc.)'. His estimate for this total category is very high in his 1992 report: 800 MJ/m^2, which is no less than 40% of the total energy use[7]! On the other hand, Srivinas and Palz/Zibetta estimate the ancillary process energy both at 200 MJ/m^2. Clearly there is considerable confusion and controversy here.

[7] Remarkably in his 1989 report the estimate for ancillary use is much lower, only 260 MJ/m^2 or 14% of the total, and 870 MJ/m^2 (48%) for direct process energy [4].

First we should look into the definition of ancillary process energy. For example by asking which energy consuming functions in the production facility should be included in this category of ancillary process energy. We can mention heating, air conditioning, lighting, work area ventilation and environmental control as examples of ancillary energy use, although the last item might also be classified as direct process energy.

Also we need a clear demarcation of the *system boundary* when asking which kind of services surrounding the production facility should be included in the analysis. What for example to do with: management and administration, maintenance staff, marketing and distribution, catering and R&D laboratories. In our opinion the first four services should be included, but the last one not.

A further complication is that even if a clear demarcation of ancillary process energy use has been made in theory, this definition may still be quite difficult to maintain in an actual measuring campaign.

All these problems regarding the definition and demarcation of ancillary process energy are probably the main cause for the observed variations in the estimates. A useful approach to arrive at better estimates might be to distinguish three categories of ancillary energy use:

(1) Energy use for process-related functions, like environmental control equipment: Here specific energy consumption data for the considered production process should be obtained. Unfortunately such data are not available at this moment.

(2) Energy use for personnel-related functions *within the production area* ('blue collar workers'). This energy is mainly used for functions like lighting, climatisation and health and safety control.
Although these figures will be rather plant- and process-specific, estimates may be possible by comparison with other manufacturing facilities. Clearly special requirements such as clean room facilities will drive up energy use in this category considerably.

(3) Energy use for personnel-related functions *outside the production area* ('white collar workers'), comprising functions like climate control, lighting, computers, etc. A quick estimate shows that the energy use in this category is probably not more than 2 MJ per m^2 of module area[8], so we may further neglect it in our analysis.

We will now try to make an estimate of energy consumption in the category 2 (and 3) in the PV industry by comparison with other industries.

From a study of energy use by function in the Dutch manufacturing industry [36]

[8] Estimates can be based on data for the energy consumption in office buildings. For a modern office building in the Netherlands the energy consumption is in the range of 300–500 MJ/yr per m^2 of floor area, while the total floor space per person is 20–25 m^2 [34]. This gives us an energy consumption of 6–12 GJ/person/yr. Direct labour requirements for a 60 MWp thin film plant are estimated at 200–350 persons [35], so if we assume that indirect labour is 30% of direct labour we have at most 100 office workers or $1.7 \cdot 10^{-4}$ man/year per m^2 module area. Combining this with the energy use of 12 GJ/person/yr obtained above yields an energy use of 2 MJ/m^2 module area for the offices.

we can derive data on the energy consumption for non-production-related operations such as space heating, climate control, ventilation, lighting and computers. In those sectors of the light industry, which might bear a certain similarity to the PV industry, the share of 'non-production energy' in the total energy use is relatively high: between 30% and 70%[9].

If we relate that the non-production energy use to the number of workers in each industry sector it appears that the non-production energy use per worker is always in the range of 43 to 54 GJ/worker/yr. An average value of 50 GJ/worker/yr for non-production energy use might thus be representative for these light manufacturing industries, and possibly also for the PV industry[10].

So a rough estimate of the personnel-related ancillary energy use (categories 2 and 3) may be made on the basis of the number of workers and the average energy use factor derived above. Assuming a total labour requirement of 2.3 man-hour per m^2 module area[11] results in an ancillary energy use of about 70 MJ/m^2.

This estimate is very low compared to ancillary process energy requirement found in the studies for module manufacturing (200–800 MJ/m^2). Note, however, that our own estimate does not yet include the *process-related* ancillary energy use (category 1 above), but seems hard to believe that this would add several hundreds of MJ/m^2.

Our tentative conclusion is that the use of 'ancillary process energy' in thin film module manufacturing is probably around 200–300 MJ/m^2 for today's plants but that it may be lower in future plants with lower labour requirements. The energy use for environmental control and other process-related ancillary energy use is not known separately but should be included in the figure above. The estimate made by Hagedorn for ancillary process energy of 800 MJ/m^2 seems much too high.

A final remark that we would like to make here, is that the ancillary process energy is very much dependent on local factors such as the climate, but also on factors like building practices and energy conservation measures. For example heat recuperation from exhaust air can significantly reduce the energy use for space heating. In this respect there is probably considerable room for reduction of the ancillary process energy use by careful design of the plant and the energy management system. In our opinion a good energy-efficiency within the PV plant itself should be taken as a challenge for an industrial sector which thanks its existence largely to the 'energy problem'.

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[9] Industry sectors that we looked at were: metal products industry (27%), mechanical engineering industry (43%), electrotechnical industry (31%), transport equipment industry (33%), instruments and optical industry (72%).

[10] Note that 50 GJ/person/yr of non-production energy use sound reasonable in comparison to the 6–12 GJ/person/yr for the energy use of office workers (see note above) and in comparison to the average household energy use of 30 GJ/person/yr.

[11] Starting with an estimate of 27 ECU/m^2 for direct labour cost [37] at a rate of 15 ECU/manhour and adding 30% of indirect labour yields 2.3 man/hour/m^2 or 0.0014 man-year per m^2. Multiplying this with an energy/worker ratio of 50 GJ/person/year gives an energy use of 70 MJ/m^2.

3.9. *Energy for capital equipment*

From the overview table we see that the estimates on energy requirement for capital equipment show very large variations: from negligible (Srivinas) to 440 MJ/m^2 (Alsema). Because the latter value is more than 20% of the total energy requirement a further investigation of this issue is important.

A large contribution from capital equipment energy is somewhat surprising if we consider the fact that in most energy analyses of industrial products the energy requirement for capital equipment contributes not more than 1–2% of the total energy requirement [32, 38].

Obviously a full energy analysis of the production of the capital equipment is impossible in the framework of a PV study. The most viable approach to make an estimate anyway is by combining statistical and economic data, namely:

(1) Statistical data on the energy intensity of various economic sectors;
Input–output analysis of energy statistics by economic sector gives a value for the cumulative energy intensity of industrial products. By cumulative energy intensity we understand here the total amount of energy which has been used to manufacture a product, divided by the economic value of that product. For the manufacture of production equipment a cumulative energy intensity in the range of 9–12 MJ/ECU[12] has been estimated, although for the manufacture of metal products and for building materials it is higher with 17 resp. 21 MJ/ECU [39, 40]. We will assume here an average value of 12 MJ/ECU for the cumulative energy intensity of the equipment and buildings necessary to produce PV modules.
(2) The investment costs for a PV plant, possibly broken down in cost for the building and for the production machinery.
In a recent study on the costs of thin film production, the total capital cost for a 60 MWp/yr production facility are estimated at 4.3–7.8 ECU per m^2 of module area produced[13]. Older estimates of capital costs for a 10 MWp thin film plant arrive at about 9 ECU/m^2 [37, 41]. Obviously, the assumed depreciation time directly determines the value for the capital cost per m^2 module. In all the costs studies above a 10 year depreciation period was assumed[14].

If we combine the capital cost estimates with the energy intensity data we arrive at an energy requirement for capital equipment of about 110 MJ/m^2 for a present-day

[12] For example: production of machinery used 10 MJ/ECU, electrotechnical industry 9 MJ/ECU, automobile industry 12 MJ/ECU, manufacture of instruments and optical goods 10 MJ/ECU. (data for The Netherlands, 1990; from: [39]). Analyses for the German economy give similar values [40].

[13] For a-Si production estimated capital costs were 4.3 ECU/m^2, for CdTe (electrodeposition) 4.8 ECU/m^2 and for CIS modules (co-deposition) 7.8 ECU/m^2. Module efficiency is assumed to be 8% for a-Si, 10% for CdTe and CIS; investments rated at 10 years linear depreciation [35].

[14] Although a 10 year depreciation period may seem long in the context of production costs estimates, it seems an acceptable value for the purpose of an energy analysis where the *technical* life time of the equipment is more relevant.

10 MWp plant, while for a next-generation 60 MWp plant it may be between 50 and 90 MJ/m^2 depending on the production technology.

Both these estimates are considerably lower than previous results from Hagedorn and ourselves. While the Hagedorn does not give details about his estimation method, the difference with our own previous study is primarily in the lower capital cost estimate (previously 35 ECU/m^2). On the other hand the above result is considerably higher than Kato's and Srivinas' estimates which are both less than 1% of the total energy requirement for the module. Kato's estimate is based on the amount of steel in the production equipment. In our opinion this latter method will underestimate the energy requirements as it does not take into account the numerous other inputs to machine production[15].

Our own estimates, on the other hand, may be somewhat pessimistic because the added value of equipment for the PV industry may be slightly higher than for production equipment in general, because of the relative newness and the small market share of typical PV production equipment.

Still, in view of the relatively high share of capital costs of PV module production (typically 10–18% [37, 41]) we feel that for the energy requirement of capital equipment a contribution of 10–15% is a much more credible estimate than 1% or lower.

3.10. *Energy for transportation, installation and decommissioning*

Some processes which are not yet regarded above are transportation of materials, installation of modules and their decommissioning after the end of the useful life.

Assuming an energy use (direct + indirect) for transportation by lorry of 2–5 $MJ/t \cdot km$ [42], a module weight of 15 kg/m^2 and an average transportation distance of 1000 km (materials to factory + module to end-user) we arrive at an energy use for transportation of 30–75 MJ per m^2 module area. This is in good accordance with the results from Lewis and Keoleian who estimate transportation energy at 43 MJ/m^2 [25].

For module installation no energy use data are available but it will probably be insignificant in comparison to the manufacturing energy use.

Regarding the treatment of modules at the end of their useful life not much hard data are available either. Depending on the module type and available technologies it may be transported to a waste dump, fed into a glass recycling process or into a process aimed at recuperation of the metal content.

Recycling of the module glass will give only relatively small energy credit as already half of the energy consumption in sheet glass production is used for the melting of the glass [33]. The total energy credit of the glass waste can be estimated at about 25

[15] It has been estimated that iron and steel input consists only 20% of the total energy requirement in machine production [40].

[16] The waste glass can be used for container glass production. The energy saving due to the input of secondary glass is about 3.5 MJ per kg waste glass [43]. Further we assume a 3 mm glass thickness ($\sim$75 kg/m^2).

MJ per m^2 glass sheet[16]. Recycling of modules with the purpose of metal recuperation will most probably cost extra energy, but no further data on such processes are available.

4. Best estimates for the module energy requirements

In the table below we have tried to distil a 'best estimate' of the energy requirements for frameless a-Si and CdTe modules (Table 4). For this best estimate we based ourselves on those data that came from well-documented studies and that are in reasonable agreement with each other. For each energy category we also give a qualitative indication of the certainty of the data, based on the variations between published estimates and the degree to which these could be explained.

We distinguish in the table between glass/glass and glass/polymer encapsulated modules, because the encapsulation type clearly influences the energy requirement for the input materials. For the total energy requirement, however, the type of encapsulation is not of major importance. However, if the cell substrate involves an additional material that is not part of the encapsulation (e.g. stainless steel), the total energy for input materials will be considerably higher.

The relatively wide range in the results for the total energy requirement is not only due to uncertainties in the estimates, but also reflects the variations that may be found

Table 4
Final estimates for the energy requirements for frameless a-Si and CdTe modules (energy values given in MJ of Equivalent Primary Energy per m^2 of module area). At the bottom row we give the range of the energy requirement estimates for a module frame as they were found in the literature

	a-Si			CdTe		
Depostion process	PECVD		Certainty of estimate[2]	ED		Certainty of estimate[2]
Encapsulation type	Glass/glass	Glass/polymer		Glass/glass	Glass/polymer	
Cell material	<40	<40	+	<40	<40	+
Substrate + encapsulation material	300–400	170–250	+	300–400	170–250	+
Processing direct	300–540	260–500	0	150–250[1]	110–210[1]	–
Processing ancillary	200–300	200–300	– –	200–400	200–400	– –
Capital equipment	100–200	100–200	0	100–200	100–200	0
Module Total (frameless)	940–1480	770–1290	0	790–1270	620–1080	0/–
Frame	50–500 MJ/m^2					+ +

[1]For CdTe cells deposited by Close-Space Sublimation the direct processing energy may be considerably higher (cf. Table 2)
[2]Notation for 'certainty of data': + + = very good, + = good, 0 = fair, – = low, – – = very low. The qualifications refer to all preceding data in the same row

in processing routes and overall plant design. The highest data uncertainty is found for the 'ancillary processing category'. Production plant surveys may help to decrease the uncertainty at this point.

Regarding the module frames we can remark that although the variation in published estimates is quite large the energy requirement for a specific module frame can be determined quite accurately if the amount and type frame material is given.

We can see that the total energy requirement for CdTe modules (electrodeposited) is estimated to be 150–200 MJ/m^2 lower than for a-Si modules. The difference with a-Si is less large than one might have expected, because of the large contributions from encapsulation materials, ancillary processes and capital equipment. Note also that we increased the high estimate for ancillary processes of CdTe in comparison to a-Si, in view of the extra environmental control measures (Cd recycling etc.). Finally we should remark that the process energy estimates for CdTe have a larger uncertainty because of the limited industrial experience. If an alternative CdTe deposition process is employed, the process energy requirement is likely to be higher than the value given above. For instance with Close Space Sublimation the process energy is estimated at 550 MJ/m^2.

5. Energy Pay-Back Time of thin-film modules

Now that we have determined a best estimate for the energy requirement of thin-film modules we can evaluate what this means in terms of the Energy Pay-Back Time (Table 5). We assume that the modules will be deployed in a *grid-connected* application with a Performance Ratio of 0.80. The module efficiency is set at 6%.

Table 5
Energy Pay Back Time of present-day thin film modules (and frames) in a *grid-connected* application under different irradiation conditions

		Energy Pay-Back Time[1] (yr)				
		a-Si module[2]		CdTe module[2,3]		
Climate/region	Irradiation (kWh/m^2/yr)	Glass/glass	Glass/polymer	Glass/glass	Glass/polymer	Frame[4]
Very sunny	2200	0.9–1.4	0.7–1.2	0.7–1.2	0.6–1.0	0.3
Mediterranean	1700	1.1–1.8	0.9–1.5	0.9–1.5	0.7–1.3	0.4
NW Europe	1000	1.9–3.0	1.6–2.6	1.6–2.6	1.3–2.2	0.6

[1]Assuming 6% module efficiency, 0.80 system Performance Ration and 0.35 conversion efficiency from primary energy to electricity;
[2]*Frameless* module, for frame see last column;
[3]Prepared by use of electrodeposition, CSS-deposition gives higher results;
[4]Assuming a frame energy requirement of 320 MJ/m^2, based on a typical aluminium frame of 0.35 kg per meter, module dimensions of 0.75 m $\times$ 1.35 m and a GER of Al profiles of 220 MJ/kg (cf. appendix).

We see from the table that under 1700 $kWh/m^2/yr$ irradiation the Energy Pay-Back Time of a present-day thin-film module, without frame, will be less than 2 years.

However, we also see that a frame may add 0.3 to 0.6 years of EPBT. So a framed a-Si module, with glass/glass encapsulation at a NW-European location can have an EPBT of 3.6 years, a time length which is rather long considering that we have not yet accounted for the support structure and cabling.

Therefore it would be good to know if there is potential for future reductions in the energy requirement, an issue which we will discuss next.

6. Future prospects

We have already considered the prospects for reductions of the ancillary process energy requirements and the energy for capital equipment.

We have seen that the ancillary process energy may be reduced by energy-efficient plant design and as a result of a decrease in labour requirements for module production. It is difficult to give a quantitative estimate of these effects.

The energy requirement for capital equipment will benefit from longer depreciation times, better equipment utilization and perhaps from reduced energy use in equipment manufacturing industry. In view of expected capital cost reductions in thin film manufacturing it seems probably that the capital energy requirement will decrease to 100 MJ/m^2 or below.

With regard to the encapsulation materials we expect that an energy reduction of 10–20% will be achieved by the 'autonomous' increase of energy efficiency in the industry itself and in the electricity supply system within the next ten years.

With regard to the choice of encapsulation materials, however, it is wise not to compromise on module life time or environmental emissions.

If new module concepts are developed in which only polymer foils are used as substrate and encapsulation material the energy requirement for encapsulation will not be dramatically lower than with glass encapsulation, unless foil thickness below 1 mm are used. For example with a total foil thickness of 3 mm the energy requirement[17] for the foils may be in the order of 250–500 MUJ/m^2.

This leaves us with the direct process energy. Here the effects of future technology developments are difficult to assess. There is of course some driving force to achieve lower energy consumption because of the associated costs. Indirectly the process energy consumption may also profit from the trend towards thinner layers and more efficient material use, because it will allow shorter deposition times. Furthermore it seems probable that a higher equipment utilization in optimized production lines will also decrease energy consumption, for example by reducing stand-by losses. Kato, for example, foresees a 50% reduction in process energy when scaling up production to 100 MW/yr [23]. In our own previous study on a-Si module production [13] we

[17] Assuming a specific density of 1.7 kg/dm^3 and a GER value of the polymer of 50–100 MJ/kg, which is the estimated GER range for materials like EVA and poly vinyl fluoride.

even expected that a 70% reduction of process energy would be feasible with future production technology. Finally, we can remark that the goals of increased module efficiency, higher stability and prolonged module lifetimes are also very important in reducing the energy pay-back time or energy return factor of a module.

Altogether we think that an energy requirement below 1000 MJ/m^2 for a thin film module is achievable within the near future, which—in combination with an increase in module efficiency—should be sufficient to bring down the EPBT to less than one year.

7. Conclusions and recommendations

Having reviewed eight different energy analysis studies for a-Si and CdTe thin-film modules we came to the conclusion that a Gross Energy Requirement below 1500 MJ/m^2 can reasonably be achieved for frameless module with present-day production technology. Assuming installation of such a module in a grid-connected PV system under 1700 $kWh/m^2/yr$ irradiation results in an Energy Pay-Back Time (EPBT) of less than 2 years. However, an aluminium frame may add up to 0.6 years to the module EPBT.

The reviewed studies sometimes showed marked differences in their estimations, but these could mostly be explained by variations in module encapsulation and cell processing. Uncertainty, however, remains in the category of ancillary process energy, and especially on the energy consumption for environmental emission control. Differences between cell types (a-Si vs CdTe) are discernable but seem relatively small. Major factors influencing the overall energy requirement of a module are the choice of materials for substrate, encapsulation and frame.

Future technology will probably achieve savings on: energy for encapsulation materials, capital equipment energy and processing energy. It seems probable that future energy requirements for a frameless thin-film module will be below 1000 MJ/m^2, so that with a concurrent increase in module efficiency an EPBT of less than one year may be expected.

To module manufacturers we would like to give the following recommendations in order to achieve production of modules with a high net energy yield:

- choose for energy-efficient equipment;
- reduce energy consumption for overhead processes, like space heating, climate control, lighting, computers;
- avoid energy-intensive materials such as (primary) aluminium;
- design the module for easy disassembly and recyclability;
- avoid heat treatments, low-pressure processes and processes with a low material efficiency.

However:

- do not compromise on module efficiency and lifetime, production yield, occupational safety or environmental emissions;

With respect to energy analysts investigating PV technology we would like to recommend:

- Aim for more clarity on:
  —system boundaries;
  —module encapsulation and framing;
  —the evaluation of ancillary process energy;
  —energy used by environmental control equipment (and other process-related ancillary energy use);
  —Gross Energy Requirements of input materials;
  —the assumed fuel mix for the electricity supply system;
- Express energy requirements:
  —on basis of module area;
  —separately for thermal energy, electrical energy and 'feedstock energy',

or:

  —as equivalent primary energy units;
- Try to indicate energy reduction options for the investigated process.

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Appendix 1
Gross Energy Requirements of some module materials. Because regional differences may be significant, the region for which the data were derived/validated are given

Material	GER (MJ/kg)	Data source	Regional validity	Certainty of energy data	Spec. density (10^3 kg/m^3)
Float glass	15	[31, 44]	W. Europe	++	2.5
Al primary	190	[32]	W. Europe, US	++	2.7
Al secondary	18	[31]	W. Europe, US	++	2.7
Al profile, anodized (from prim. mat.).	220	[25, 31, 32]	W. Europe, US	++	2.7
EVA	75	[31]	W. Europe	0	0.9
PVF-foil ('Tedlar')	115	[31]	W. Europe	0	1.8
Stainless steel foil	69[2]	[25]	US	+	8
Steel back plate (galvanized)	45[2]	[25]	US	+	8

[1]Notation for 'certainty of data': ++ = very good, + = good, 0 = fair, – = low, – – = very low
[2]Calculated back from data in [25].

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